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Final Report
Compton Gamma Ray Observatory Phase 4 Guest Investigator Program
Solar Flare Hard X-ray Spectroscopy
Dr. Richard Schwartz¹

¹Laboratory for Astronomy and Solar Physics/Goddard Space Flight Center, Greenbelt, MD 20771
 (Hughes STX Corporation)

Introduction

During the Compton Gamma-Ray Observatory's (CGRO) Cycle 4 Guest Investigator Program we proposed three mutually supporting efforts to support the analysis of BATSE solar flare data with a particular emphasis on hard X-ray spectroscopy—building upon our Cycle 2 and 3 efforts. The efforts included:

- (1) The continued improvement of a software and database environment capable of supporting all users of BATSE solar data as well as providing scientific expertise and effort to the BATSE solar GI community.
- (2) The continued participation with the PI team and other Guest Investigators in the detailed analysis of the BATSE detectors' response at low energies.
- (3) The first systematic study of the Super Hot Component of solar flares using late phase hard X-ray spectra from 10-40 keV.

We successfully completed our first two goals in the Cycle 4 period, providing essential scientific analysis, software, and data support to several investigations using BATSE Data (especially studies using electron time-of-flight differentials lead by Dr. Markus Aschwanden), and providing expertise in calibrating the BATSE low-energy Spectroscopy Detectors. It was discovered during the attempted to understand BATSE Spectroscopy Detector (SPEC) measurements at low energies, that studies of the Super Hot Component would be suspect until more was known about the response and calibration of the SPEC detectors. Our efforts have resulted in the publication of several papers using electron time-of-flight measurements to suggest a cusp sight for particle acceleration in solar flares, the impending release of the SPEX Spectroscopy Analysis package onto the SolarSoft collaborative solar software library, a better understanding of the response of the BATSE Spectroscopy Detectors as well as groundwork for future calibration efforts, and the publication of several research papers supported by Dr. Schwartz's work under the Cycle 4 program.

Software Development and Scientific Support for BATSE Research

Dr. Schwartz supported several studies of BATSE flare data during Cycle 4, by providing both scientific and software/data expertise. The SPEX software package for spectral analysis of BATSE, Yohkoh(WBT/HXT), SMM/HXRBS, and HIREX spectroscopy data was enhanced during Cycle 4 to support remote users, provide help, and plot error residuals for model fits. Using our software and expertise, several scientists and students carried out research on BATSE Flare data, including:

- Brian Park, Stanford University: Using SPEX for solar research (paper in preparation),
- Terry Kucera, NASA: Using SPEX and BATSE SPEC database to determine the characteristics of energetic electrons in solar flares, comparing thermal and non-thermal models (paper in preparation),
- Haimin Wang, NJIT: Comparing microwave and H-alpha observations at the hard x-ray peak of the 1992 January 13 limb flare (Wang, 1995, 1996), and
- G. Cauzzi: Multi-spectral analysis of the 30 June 1991 solar flare (Cauzzi, 1995).

Dr. Schwartz has also supported investigation of the thermal/non-thermal model by Zarro, and the investigation of the June 1991 flares by Share and Murphy. We have also continued support of the joint analysis of the 30 June 1991 flare seen with GRANAT and CGRO looking at the event up to 30 MeV and

extending the GRANAT spectral coverage to low energies using BATSE. Lastly, one of the most productive uses of the expertise provided under this grant was the discovery of electron time-of-flight measurements in BATSE hard X-ray data, which is discussed in the following section.

Exploiting Electron Time-of-Flight Measurements

With our assistance, Dr. Markus Aschwanden of the University of Maryland made extensive use of the SPEX spectral fitting software developed and installed by Dr. Schwartz, to lead a comprehensive analysis of BATSE solar flare data. This research resulted in the discovery and exploitation of electron time-of-flight measurements, allowing us for the first time to trace electron acceleration sites and electron kinematics in solar flares. The complete dataset of solar flares simultaneously observed with BATSE in high-time resolution mode (64 ms) and the Hard X-Ray Telescope (HXT) on board Yohkoh, was used to determine the electron time-of-flight (TOF) distance and the flare loop geometry in 42 events. The electron TOF distances were determined from time delays of ($\sim 10 - 100$ ms) hard X-ray (HXR) pulses (measured in 16-channel spectra over ($\sim 20 - 200$ keV), produced by the velocity difference of the HXR-producing electrons. The flare loops were mostly identified from double footpoint sources in ~ 30 keV HXT images, with radii ranging from $r = 3000$ to $25,000$ km. We found a scaling law between the electron TOF distance Δ and the flare loop half length $s = r (\pi/2)$, having a mean ratio (and standard deviation) of $\Delta/s = 1.4 \pm 0.3$. In 5 flares we observed coronal ~ 30 keV HXR sources of the Masuda-type in the cusp region above the flare loop, and found that their heights are consistent with the electron TOF distance to the footpoints. These results provide strong evidence that particle acceleration in solar flares occurs in the cusp region above the flare loop and that the coronal HXR sources discovered by Masuda et al. are a signature of the acceleration site, probably controlled by a magnetic reconnection process. These results have been expanded upon and analyzed in several papers published in the *Astrophysical Journal* and other publications (Aschwanden, et al. 1996a). Figure 1, below, provided a graphical representation of the cusp source suggested by electron time-of-flight results.

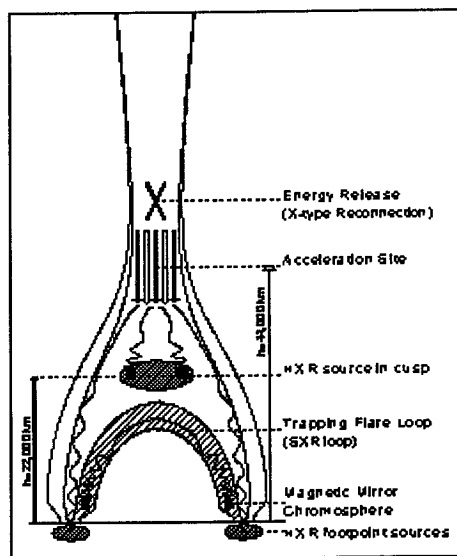
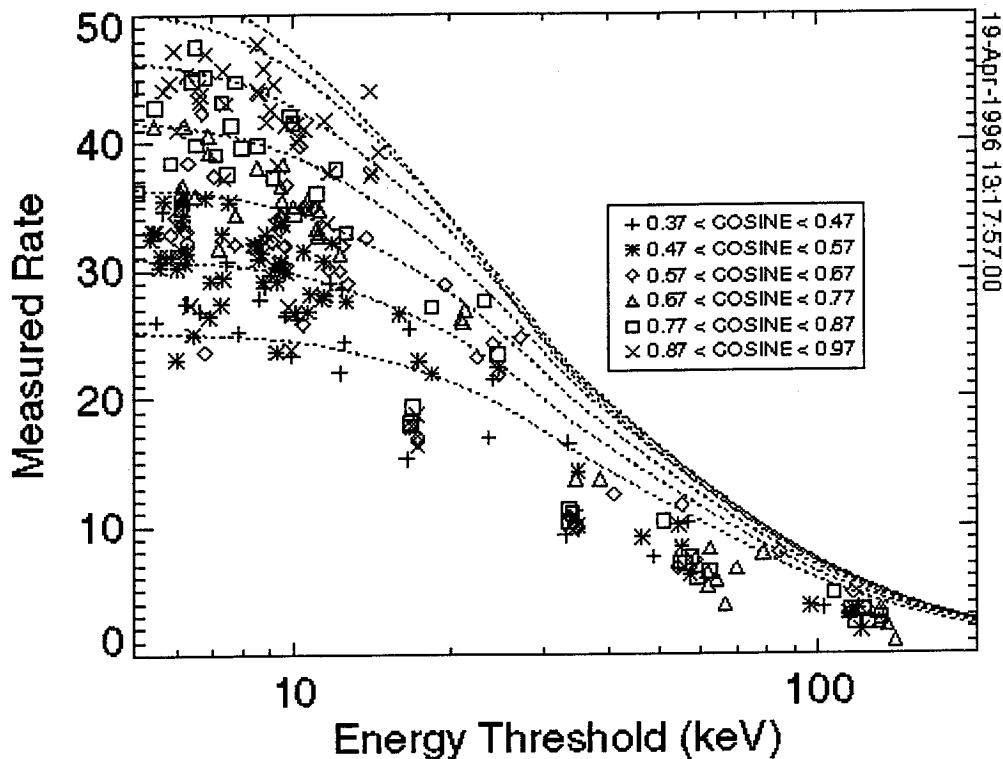


Figure 1. Cartoon of a possible flare scenario for the Masuda Flare, constrained by the height of the acceleration source inferred from the HXR timing.

Understanding the BATSE Spectroscopy Detectors

Under Cycle 4, BATSE SPEC DISCSP data of several thousand Earth occultation time-intervals of the Crab have been processed into a calibration database which has contributed to the understanding of the low energy response of the BATSE SPEC detectors. These intervals have been analyzed using a very straight forward technique where the observed count rate is fitted to a linearly varying background and a step at the time of the occultation over a several minute interval. The few seconds of the transition itself are discarded as well as any single time interval outliers which presumably are noise-spikes and not intrinsically from the Crab, the well-measured fiducial source of X-ray astronomy (we compare to the HEAO A-4 measurements by Jung 1989). This data set can be expanded 6-fold using the entire mission history of DISCSP data. The current work already contributed to a revision in the standard detector response functions. Figure 2 (below) shows the current status of these measurements and their comparison to predicted values. Each data point represents one observing interval with a single instrument gain and spacecraft orientation where the different symbols indicate the range of zenith angles. The dotted lines show the expected response as a function of integrated response above the Energy Threshold measured in counts/s for each of the ranges of zenith angle. While there is reasonable agreement in integrated response at low energy, there is significant disagreement between the expected and observed values above 15 keV where it is hoped that additional observations will clarify the situation.

Figure 2.



Conclusion

Our efforts under the Cycle 4 Guest Investigator program have led to a greater understanding of the BATSE instrument and the processes which drive solar flares. We have provided an easy to use, flexible software package which has been used by several researchers to study the BATSE Spectroscopy data, provided essential support to research which led to the discovery and exploitation of electron time-of-flight differences in solar flares, and provided the support to make more precise measurements of the SPEC detector response as well as build for future efforts to calibrate this valuable set of data.

Publications Supported by Dr. Richard Schwartz from CGRO Cycle 4

- "The Scaling Law between Electron Time-of-Flight Distances and Loop Lengths in Solar Flares," Aschwanden, M. J., Hudson, H. S., Kosugi T., & Schwartz, R. A. 1996a, **ApJ**, submitted
- "Electron Time-of-Flight Measurements During the Masuda Flare 1992 Jan 13," Aschwanden, M. J., Hudson, H. J., Kosugi, T., & Schwartz, R. A. 1996b, **ApJ**, 464, in press
- "The Inversion of Electron Time-of-Flight Distances from Hard X-Ray Delay Measurements," Aschwanden, M. J., & Schwartz, R. A. 1996c, **ApJ**, 464, in press
- "Studying the Thermal/Nonthermal Electric Field Model Using Spectral and Spatial X-ray Data from CGRO and Yohkoh", Kucera, T., Love, P., Dennis, B., Holman, G., Schwartz, R., & Zarro, D. 1996, in preparation.
- "OVRO, BBSO, BATSE, and Yohkoh Observations of a Twin Solar Flare," Wang, H., Gary, D. E., Zirin, H., Nitta, N., Schwartz, R. A., & Kosugi, T. 1996, **ApJ**, 456, 403
- "Accuracy, Uncertainties, and Delay Distribution of Electron Time-of-Flight Measurements in Solar Flares", Aschwanden M. J., & Schwartz, R. A. 1995, **ApJ**, 455, 699
- "Solar Electron Beams Detected in Hard X-ray and Radio Wavelengths," Aschwanden M. J., Benz, A. O., Dennis, B. R., & Schwartz, R. A. 1995, **ApJ**, 455, 347
- "Coordinated OVRO, BATSE, Yohkoh and BBSO Observations of the 1992 June 25 M1.4 Flare," Wang, H., Gary, D. E., Zirin, E. H., Schwartz, R. A., Sakao, T., Kosugi, T., & Shibata, K. 1995, **ApJ**, 453, 505
- "Electron Time-of-Flight Differences in Solar Flares," Aschwanden, M. J., Schwartz, R. A., & Alt, D. 1995, **ApJ**, 447, 923
- "Coordinated Studies of Solar Activity Phenomena I- The observational program and the flare of June 7, 1991," Cauzzi, G., Falchi, A., Falciani, R., Smaldone, L., Schwartz, R., & Hagyard, M., 1995, **Astron. and Astrophys.**, 299, 611
- "The microwave and H-alpha sources of the 1992 January 13 flare," Wang, H., Gary, D. E., Zirin, H., Kosugi, T., Schwartz, R. A., & Linford, G. 1995, **ApJ Lett.**, 444 (No. 2), L115

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